The Pivotal Role and Current Status of Nondestructive Inspection Systems in the Maintenance of Aging Aircraft

J.P. Gallagher, W.C. Hoppe, Alan Berens, David Stubbs
University of Dayton Research Institute
University of Dayton, Dayton, OH 45469, USA

Charles Buynak
Nondestructive Evaluation Branch
Materials and Manufacturing Technology Directorate
Wright Patterson AFB, OH 45433, USA

Abstract

This paper discusses the pivotal role that Nondestructive Inspection (NDI) plays not only for maintaining safety through early crack detection in airframes and engines, but also for minimizing corrosion maintenance costs. The paper is based on multiple projects that have supported developing and validating NDI systems for crack detection in airframe and engine components and for corrosion detection in airframe structures. These projects have led to a new understanding of how to develop advanced (automated) NDI systems and how to quantify the capability of an inspection system for accurately detecting crack damage or corrosion damage in a maintenance environment. The paper also addresses the issues associated with how reliable, accurate NDI can also be used to detect (and quantify) the early stages of corrosion damage, so that corrosion control strategies can be implemented.

1. Introduction

Safety and economic issues drive the creation of maintenance plans for aging aircraft [1]. Over the last 30 years considerable development has taken place to ensure the effective management of potential crack damage on the structural integrity of aircraft and engine structures. The importance of nondestructive inspections (NDI), as part of the early crack detection maintenance approach to safety for these flight critical structures, is well recognized and practiced [2]. In contrast to cracks, the economic impact of corrosion on the maintenance of an aging aircraft is probably more significant than the safety impact, especially when one considers the costs for sustaining military transport aircraft. Thus, as the fleet of aircraft age, corrosion becomes a significant driver in airframe maintenance planning [3].

Over the years, statistically valid approaches have been developed to quantify the probability of detection (POD) for cracks using any given inspection system and these POD assessments have been employed in a growing number of applications [4,5]. Only now are similar POD assessments being attempted in order to quantify the capability of an NDI system for detecting corrosion; and this is possible, only because the current NDI metrics can be used to quantify the impact of corrosion damage on the structure [6].

Paper presented at the RTO AVT Specialists' Meeting on "Life Management Techniques for Ageing Air Vehicles", held in Manchester, United Kingdom, 8-11 October 2001, and published in RTO-MP-079(II).

As aircraft age, structural maintenance actions are required to ensure the continuing safe and economical operation of both the airframe and engine. These maintenance actions are required to contain the level of in-service created fatigue and corrosion damage below that which could (1) compromise aircraft structural integrity or (2) cause premature replacement of significant structural components. The USAF uses the Force Structural Maintenance Plan (FSMP) and the Engine Structural Maintenance Plan (ESMP) to summarize the anticipated actions and the times when known or suspected problems will be addressed in the airframe and engine, respectively. Initially, these documents are based on information generated during the design phase and then updated periodically as field experience is gained.

1.1 Principal Reasons Why NDI is Pivotal

The FSMP and ESMP define safety related surveillance programs that identify the presence of crack damage at some fraction of the expected crack growth life. NDI provides an essential tool for ensuring that any crack damage is found well before it could reach a size that would impact safety. Inspecting the structure for crack damage provides an alternative to replacing expensive structural elements on a strict time schedule such as dictated by a safe life approach. When NDI indications identify the occurrence of cracks, prescribed repair actions are triggered. In essence, NDI systems provide the basis for condition-based structural maintenance.

One important aspect of this surveillance is that the damage is sometimes found in known hot-spot locations well before it was anticipated. A basic feedback loop is required to provide the engineers responsible for keeping the FSMP and ESMP current with early observations of anticipated damage in aging aircraft. An effective feedback loop will allow the timely rescheduling of planned maintenance and repair actions or the development of new actions if hardware must be replaced.

To support aging aircraft, the maintenance plan must evolve, since unanticipated damage can be created during in-service operations; and, this damage is only found by experience. In-service, age-related damage (fatigue, corrosion, environmental degradation and wear) frequently occurs at unanticipated locations, and many times the damage is found by happenstance. It is important that this unanticipated in-service damage information be rapidly transmitted from maintenance operations to the FSMP/ESMP engineers.

Timely feedback on unanticipated damage will allow the maintenance and structural engineers to devise strategies for (1) establishing the breath of the potential problem and (2) developing and implementing cost-effective maintenance or repair actions. Having an effective inspection procedure that identifies the damage (before it reaches a structural limit) and a repair procedure that arrests (or slows) the growth of damage and reestablishes the integrity of the structure is the preferred approach for addressing unanticipated damage, and much more economically attractive than replacing hardware.

Thus, NDI is essential for routine surveillance to locate anticipated damage, for routine surveillance to detect unanticipated damage and for scoping the extent of any newly identified in-service damage problems. The NDI surveillance and problem solving activities that determine the presence of aging damage provide the maintenance manager with the ability to anticipate when major fleet-wide maintenance actions are required.

1.2 Crack Detection NDI Reliability – Driven by Safety

The reliability of crack detection NDI systems is driven by safety. Damage tolerant design assumptions require that crack size assumptions following an inspection are equal to the demonstrated probability of detection (POD) capability of the system. The POD is thus an important quantitative measure of the NDI system reliability. The POD established damage-tolerant crack size values are typically given as the 90/95 (probability of detection/ confidence level) crack sizes. For automated inspections of engine structure, the 90/50 crack size is used. The purpose of having a 90 percent probability of detection is to ensure that the inspection system will detect a critical flaw size with a high probability (only 1 in 10 cracks of this size will be missed). So the reliability for crack detection is driven by a need to qualify the inspection performance for safety reasons.

Guidelines for assessing NDI system reliability for crack detection are available in Military Handbook 1823 [7, 8]. This handbook represents an advanced development of NDI reliability assessment for detecting cracks in critical structural components. This handbook was developed to support the retirement for cause (RFC) program and provided the basis for establishing the reliability of the RFC NDI systems used to detect cracks in USAF F100 engine disks. Figure 1 provides a photograph of one of the RFC – Eddy Current Inspection Systems used to inspect F100 engine disks. An example describing the development of the 90/50 crack-size to balances the need for crack detection reliability (limited number of misses) with an assurance that cracks will be found if there is an indication (limited number of false calls) is presented in Figure 2.

1.3 Corrosion Detection NDI Reliability - Driven by Economics

Corrosion detection NDI reliability is driven primarily by the need to find hidden corrosion economically. There are two aspects to the corrosion NDI system requirement: (1) the system must detect corrosion reliably so that significant corrosion is found, and (2) the system must not indicate the presence of corrosion when no corrosion exists (false call) to avoid unnecessary disassembly.

The state-of-art for quantified corrosion detection is about 15 years behind that of cracks. Only recently have methodologies started to evolve that allow structural engineers and NDI engineers to communicate. The basic need for quantification of the NDI system was realized about five to seven years ago, and NDI researchers have been diligently working with structural and corrosion engineers to establish metrics that measure the impact of corrosion damage on the structural performance. Today, there is still no agreement on a standard approach for quantifying the level of corrosion damage, but there are approaches, some of which will be explored further in this paper.

The following sections of the paper discuss how the experience gained in developing and applying reliability assessments to the NDI techniques used to detect cracks in engine components have been applied to NDI techniques use for other aircraft structures.

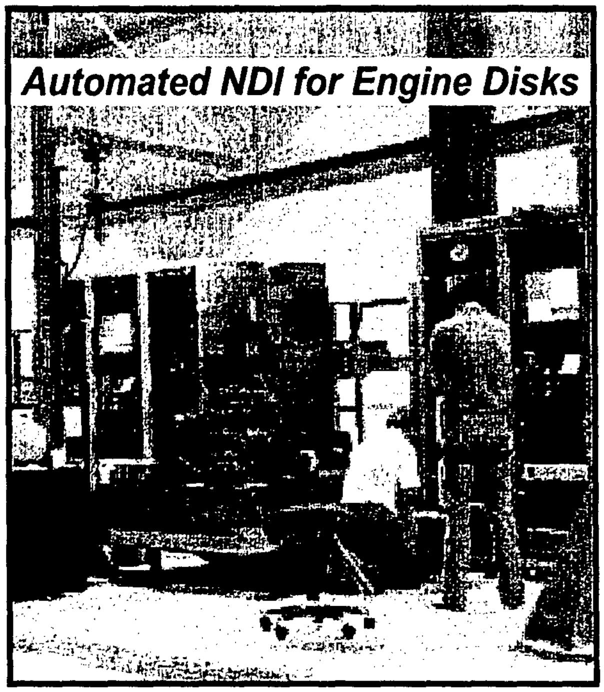

Figure 1 The modular eddy current inspection system (ECIS) is used to conduct surface inspections of USAF engine components.

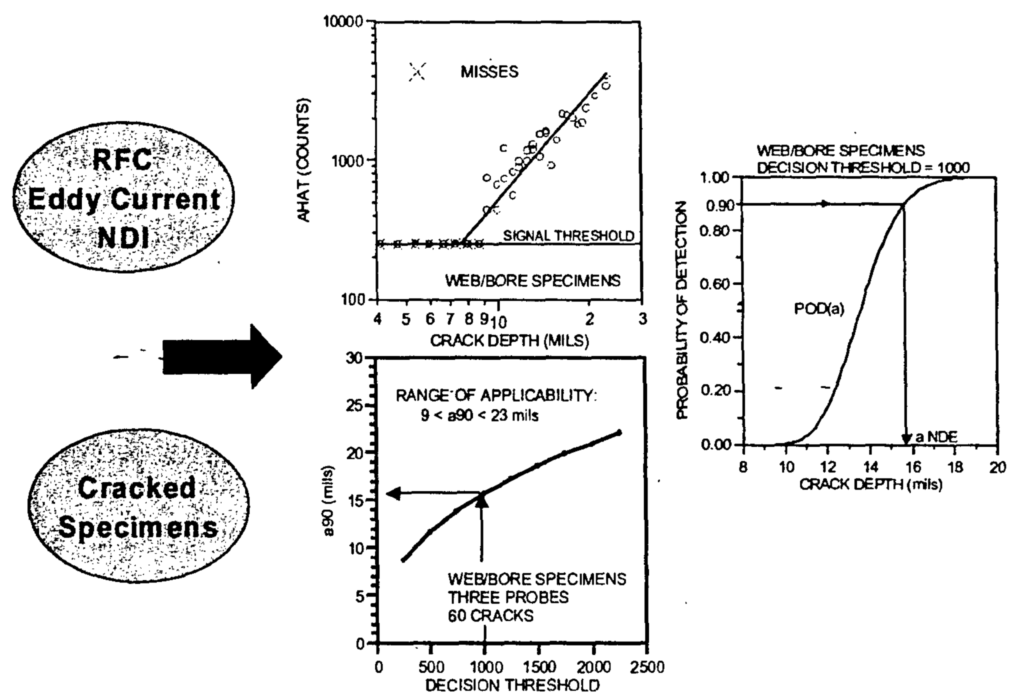

Figure 2 NDE capability improvements – detectability vs. throughput

It is important that NDI system reliability for corrosion detection be quantified. The concept of probability of detection is still an important measure of an inspection capability and the system's reliability. However, multiple opinions exist as to what must be detected. Therefore at this time, a fundamental need exists for a standard methodology that can be used to assess the capability and reliability of an NDI system for detecting corrosion damage. There is a basic and serious need for a standard that is accepted by the structures, corrosion and NDI communities, so that NDI capabilities can be evaluated for their usefulness.

1.3.1 The Metrics used for Corrosion NDI

Some of the controversy concerning standardization of NDI system for corrosion detection results from lack of agreement as to what is corrosion damage and exactly what impact does this corrosion damage have on the integrity of the structure. Fundamentally, any metric that is used to measure the capability and reliability of a NDI system for corrosion detection should have the following characteristics; the metric should: (1) measure the severity of damage, (2) have a structural impact ("effect of defect") and (3) consider the NDI system sensitivity. Because corrosion damage can take many forms (pitting, exfoliation, uniform/generalized, crevice, etc.), the metric has to be defined for the particular type of corrosion that is being experienced. For example, to characterize the effect of crevice corrosion in lap joints and doublers, one might utilize: (a) thickness loss, (b) joint pillowing, (c) surface roughness, or (d) pit depth. As another example, to characterize the effect of intergranular and exfoliation corrosion that occurs around steel fasteners in aluminum structure, one might utilize: (a) radial extent of the damage from the fastener hole or (b) the radial area of the damage from the fastener hole. Figure 3 provides two examples of metrics that may be used to quantify the structural impact of corrosion damage for the cases of a lap joint (crevice corrosion) and a fastener (exfoliation). [8, 9]

1.3.2 Concept of NDI Detection Reliability for Corrosion

The UDRI [8, 10-13] has taken the approach of developing a probability of detection (POD) for corrosion damage analogous to that for cracks. If one is using the thickness loss metric to characterize the level of corrosion damage in a lap joint structure, then the POD curve might look like that shown in Figure 4. As Figure 4 indicates, there are three zones in which structural and corrosion engineers have interest. The most important zone is on the right hand side of the chart where the level of corrosion damage has reached some critical structural or maintenance limit. If the corrosion detection capability is not high (i.e., POD<90%) for this limit, there is a strong possibility that the damage will be missed and serious economical consequences might result. Consider for example, the case where the limit is established for a blending operation – if the inspection capability is not capable of finding this type of damage, and if corrosion is present, the next time that an inspection is conducted, the level of damage may be such that structural elements will need to be replaced.

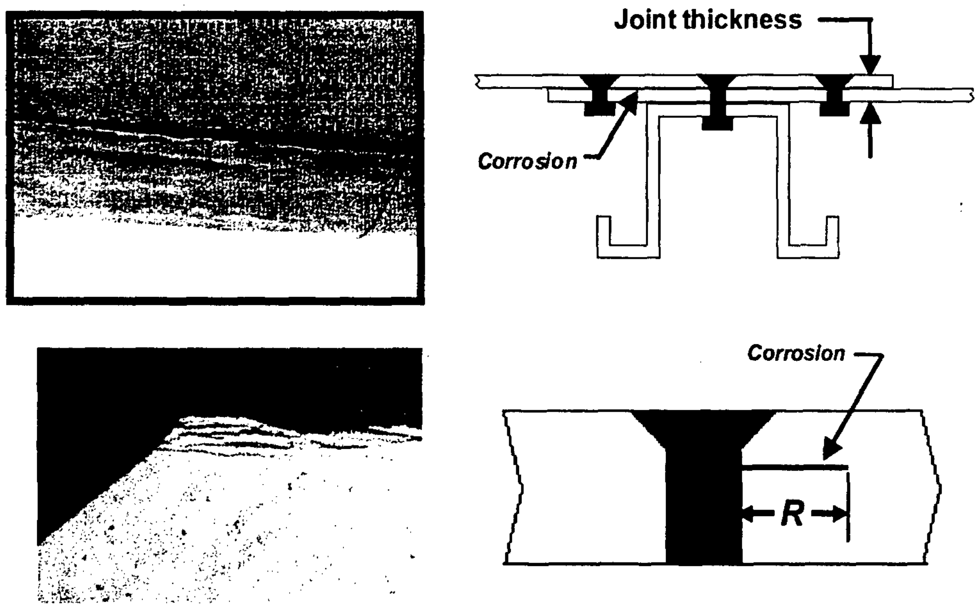

Figure 3 Lap joint and exfoliation Corrosion damage metrics [8, 9]

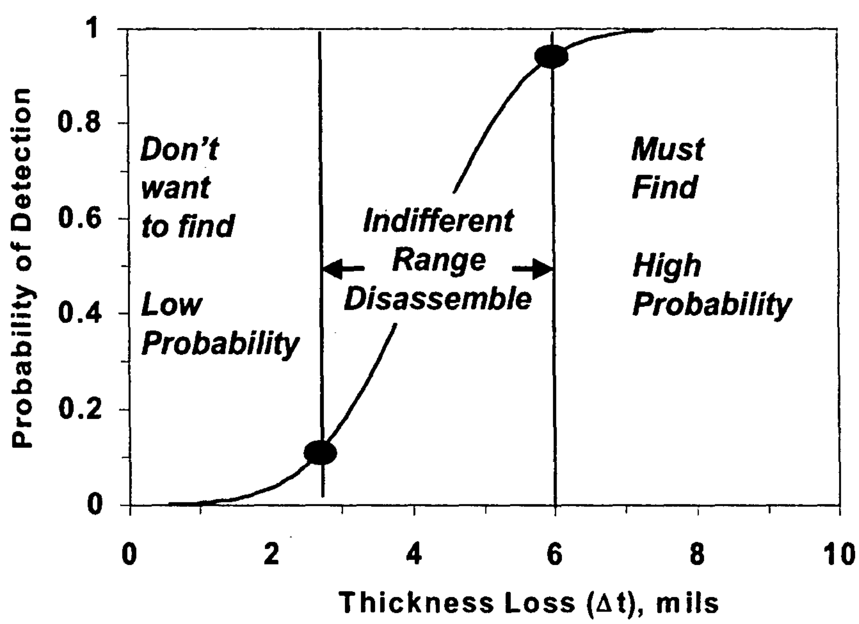

Figure 4 Corrosion POD – for corrosion control of hidden damage

The other two zones on the POD curve illustrate that the inspector also has a chance to find corrosion below the target structural or maintenance limit, although as one can note the probability of detecting corrosion damage below the target limit decreases with thickness loss. The importance of the slope of the POD curve becomes obvious. When the POD curve is not steep, not only does the chance to detect the presence of any corrosion damage decreases, but the chance of disassembling structure without finding corrosion damage also increases.

1.3.3 Developing the Assessment Methodology for Corrosion POD

The UDRI has been working both as a prime and subcontractor supporting the development and demonstration of methodology that can be used to assess the NDI system's capability for detecting corrosion damage [8, 9]. The suggested approach is based on the crack detection approach with the appropriate selection of the metric, and is patterned after the crack detection assessment methodology outlined in Military Handbook 1823. A major requirement of this methodology is that one must standardize the measurement of corrosion by type. Figure 5 diagrams the evaluation process patterned after Military Handbook 1823. The differences between the crack detection methodology and that associated with corrosion detection are shown in bold italic in the figure.

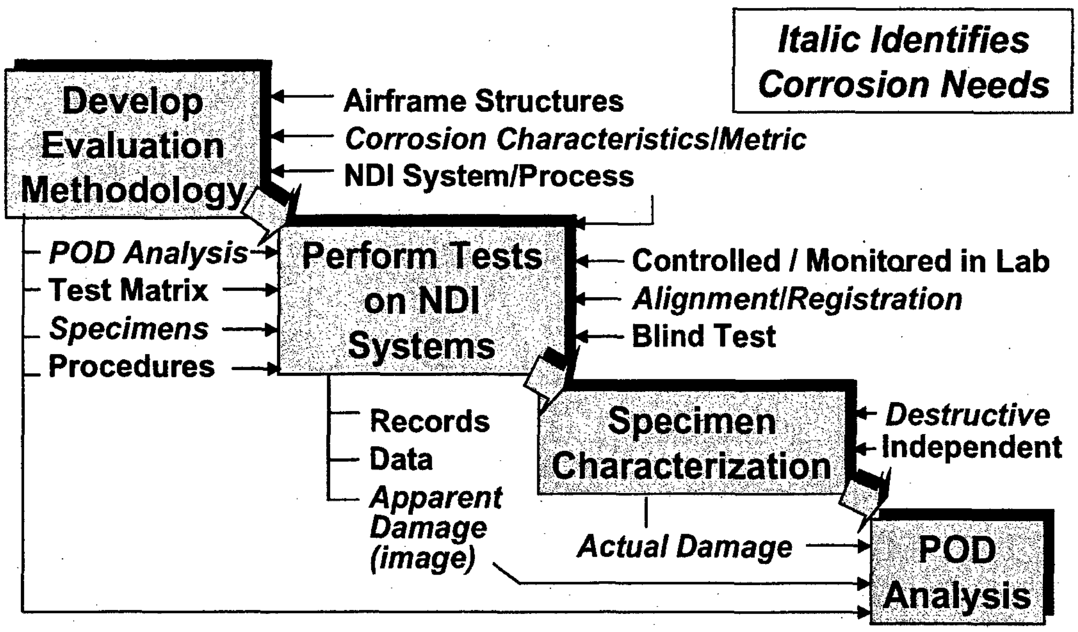

Figure 5 Corrosion NDE/I evaluation process patterned after Military Handbook 1823 for cracks

2. Addressing NDI Needs

2.1 Reducing the Inspection Burden

Over the last 20 years, the developers of NDI systems have taken a systems engineering approach to their designs. Several of these modern systems are modular, in that they: (1) process eddy current and ultrasonic signals depending on the sensor, (2) display the results in the same format, and (3) capture the data digitally so that the inspection results can be archived or reviewed off-line. See Table 1 for examples and Figure 1 for an example engine inspection station. These modern NDI systems are focused on automating the inspection processes as much as possible, since it has been demonstrated that the probability of detection (POD) for cracks is substantially enhanced when automated NDI systems replace manual inspection systems. The advantage of having an NDI system with multiple sensing and data processing capability is that the maintenance organization would eliminate the large number of NDI specialty systems purchased and could standardize their inspector training using the modular system.

Table 1
Examples of Modern NDI systems

System	Manufacturer	Advanced Capability
Retirement for Cause (RFC) for engine disks a.k.a. Eddy Current Inspection System (See Fig. 1)	Veridian Engineer	Highly automated; Digital output Historical database
Mobile Automated Scanner (MAUS) System	Boeing – Phantom Works	Eddy Current and Ultrasonic Sensors, Digital output
Ultra Image System	SAIC - Groton	Eddy Current and Ultrasonic Sensors, Digital output
High Resolution Real-time Digital X-ray System with Amorphous Detectors	GE	Digital Output Digital X-ray mode

2.2 NDE/I Specific Corrosion Needs for Airframe Structures

As discussed above, tremendous costs are incurred when corrosion damage needs to be detected in hidden locations. Limited NDI capability currently exists to detect the level of corrosion damage beyond the first layer of structure and, therefore, the only recourse for maintenance organizations is to disassemble the structure to determine if any damage is present. Where this limited capability exists, we must expand our research efforts to attack second and third layer corrosion to minimize the disassembly of non-corroded structure. Alternately, since there is some probability that corrosion damage will not be present at targeted locations, it behooves the structural community to better anticipate those locations that are actually experiencing corrosion attack, so that those which are not expected to be experiencing corrosion not be disassembled. This approach certainly helps to reduce the inspection burden (and therefore cost) of disassembly and reassembly without finding corrosion damage.

2.3 The Automated Corrosion Detection Program (ACDP)

In 1997, UDRI began a program with the USAF to develop and implement automated corrosion detection, principally in support of the KC-135 aircraft. A primary goal of this program was to develop a standard method of evaluating NDI corrosion detection capability for ultrasonics, eddy current, radiography and thermography. The focused approach was to determine if the assessment methodology of Military Handbook 1823 could be applied to lap joint corrosion with a target of detecting corrosion damage that resulted in less than a 10% thickness loss. A combination of engineered specimens and KC-135 fuselage structural joints were used to assess and demonstrate the assessment methodology and the corrosion capability. These demonstration specimens are illustrated in Figure 6.

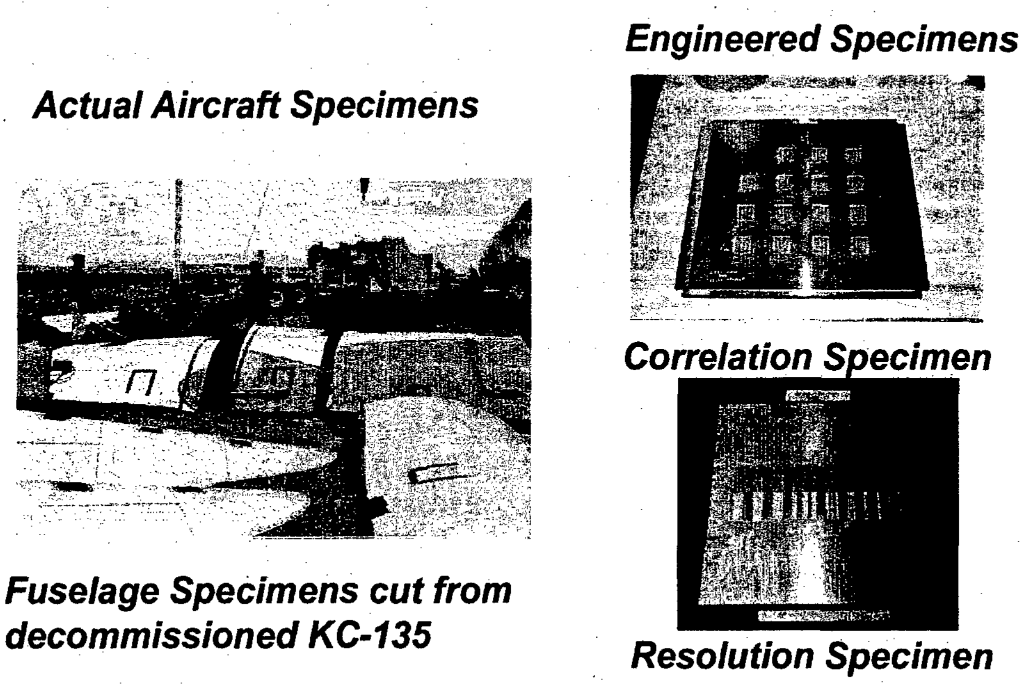

Figure 6 Actual and engineered specimens used in automated corrosion detection program

Thickness loss was selected as the metric for crevice corrosion in lap joints and doublers because thickness loss has a direct structural impact on the stresses in the joint. The evaluation followed the Military Handbook 1823 approach adapted to using the corrosion metric (see Figure 5 for an overview of this adaptation). Controlled tests were conducted on ten inspection systems representing four different inspection technologies. Table 2 summarizes the systems evaluated and the technologies on which they were based. Each of these technologies is sensitive to thickness loss either directly or indirectly.

Table 2
List of Corrosion Detection Systems, Techniques and Developers/Participants Evaluated During the Automated Corrosion Detection System

Corrosion Detection System	Technique	Developers / Participants
MOI II	Eddy Current	Physical Research, Inc.
MAUS IV	Eddy Current	Boeing/AFRL
Ultra Image IV	Eddy Current	SAIC
COREX I	Radiography	ARACOR
Reverse Geometry X-Ray ®	Radiography	Digiray/NASA Langley
Thermal Imaging	Thermography	Wayne State University
Line Scan Thermography	Thermography	NASA Langley
PULSE	Ultrasonics	AS&M, Inc.
Ultraspec	Ultrasonics	Southern Research Institute (SRI)
Ultra Image IV	Ultrasonics	SAIC

- Except for the radiography techniques, the NDI system sensitivity was to the thickness loss in the top layer of the four-layer lap joint.

Figure 7 summarizes the method used to compare the t-hat (NDI response) with t (the actual thickness). In Figure 7a, each cell (denoted by "C"), defined by the system's special resolution, in the corroded joint represents an opportunity to correlate the corrosion damage of that cell (the average change in thickness) with a measurement of the NDI response (a single t-hat value) in the location of the image (denoted by the point "P"). Because NDI systems summarize their corrosion findings with images that can cover a wide area, it was possible to develop a scheme whereby the detection of corrosion in each cell could be considered independent of detecting corrosion occurring elsewhere. The collection of independent t-hat vs. t responses are collected and summarized in Figure 7b. The POD shown in Figure 7c is derived from regression analysis. The scatter about the mean t-hat response is used to calculate the probability of t-hat exceeding the detection threshold as illustrated in Figure 7b.

2.4. Corrosion Assessment Results

In the Automated Corrosion Detection Program (ACDP), the procedures described in Figure 7 were applied to all the techniques and NDI systems listed in Table 2. Figure 8 presents the results from one evaluated NDI system based on eddy current technology. Hoppe et al. [8] recently summarized the POD curves and t-hat vs. t behaviors for all the systems and techniques. Table 3 summarizes the results obtained from some of the NDI systems that looked the most promising. Both the 90 and 50 percent probability of

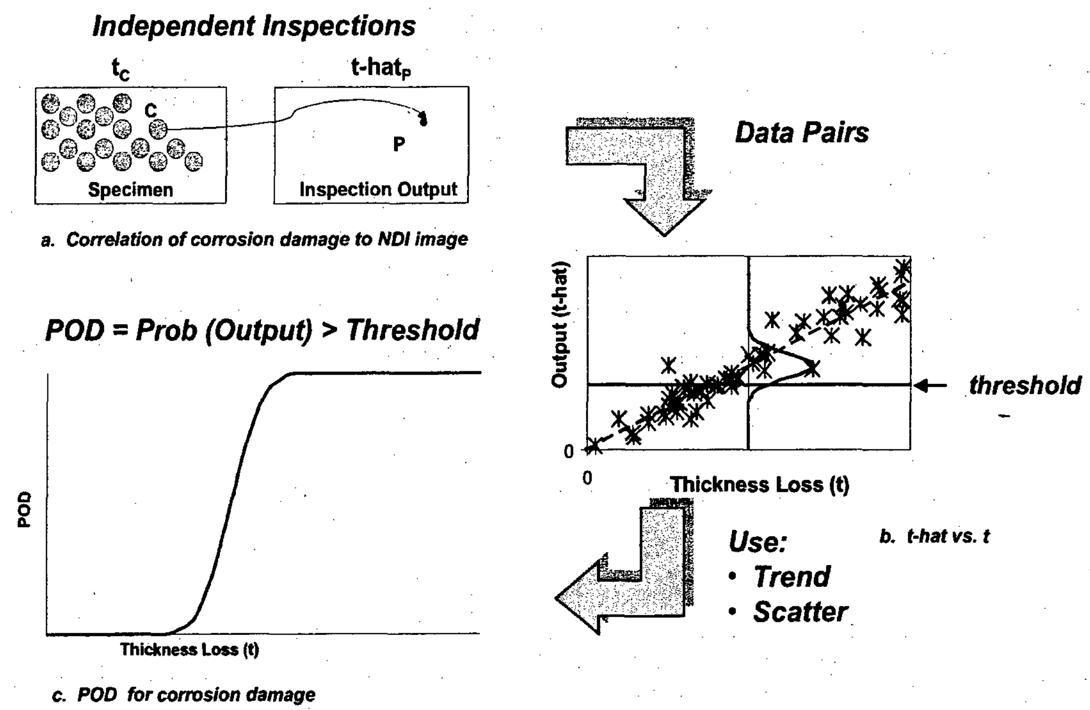

Figure 7 Formal evaluation process and methods used in automated corrosion detection program.

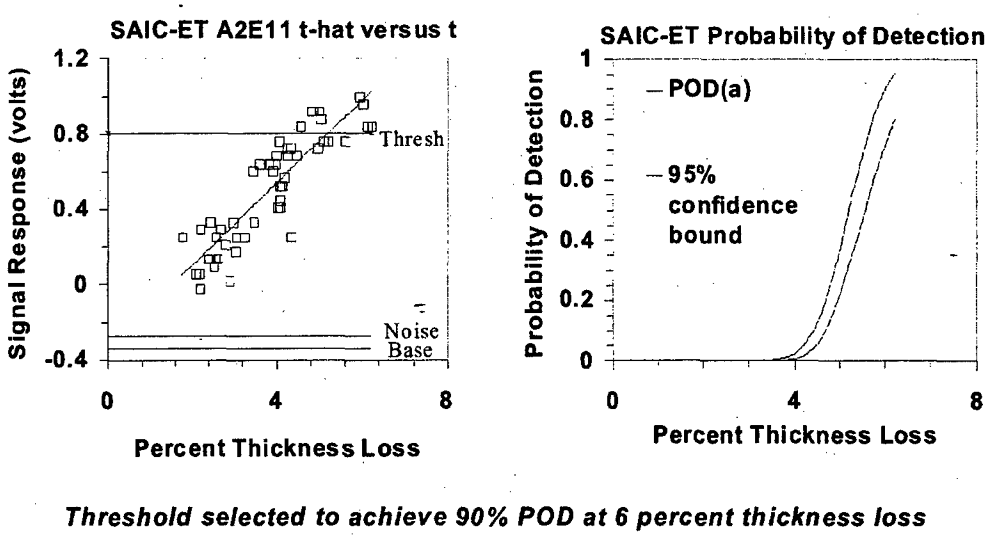

Figure 8 SAIC Ultra Image IV (eddy current) evaluation the using the ACDP method [8].

detection numbers are provided in the table along with the normal distribution parameter sigma and the signal-to-noise ratio. Sigma is related to the steepness of the POD curve, smaller values of sigma imply that the curve is steeper. Noise was estimated from zero thickness loss regions on a specimen without corrosion. Signal-to-noise measures the degree to which the threshold exceeds the noise level. One might note that the signal-to-noise ratios for the eddy current systems are, in some cases, about an order of magnitude larger than that of the ultrasonics systems. For Table 3, comparisons are for only the top thickness (0.063 inch, 1.5 mm) in the four- layer lap joint specimen. One observation made subsequent to the study was that POD comparisons between different systems are difficult due to the differences in cell size required in order to match the resolution of the NDI system.

Table 3
Summary of percent thickness loss parameters and signal to noise ratio

Manufacturer/Technology	Δt_{90} (%)	Δt_{50} (%)	$\Delta t_{90}/\Delta t_{50}$	Sigma	Signal /Noise
SAIC Ultra Image - Eddy Current	6.0	5.2	1.15	0.62	17
Boeing MAUS - Eddy Current	6.0	5.0	1.20	0.77	25
AS&M - Ultrasonics	5.6	4.0	1.40	1.11	2.2
SAIC Ultra Image - Ultrasonic	5.6	4.1	1.37	1.19	3.7
Southern Research Inst. - Ultrasonic	6.0	4.6	1.30	1.27	9.2

2.5 Near-Term Objectives for Evaluating NDI Capability

Because data were collected for both engineered specimens and real aircraft lap joints, one near-term assessment measure being pursued is the construction of diagram such as shown in Figure 9 which allows for a direct comparison between the POD values obtained from a typical laboratory type of experiment (Best) and that obtained from the an aircraft component (Standard). It is suggested that comparisons between the 90/95 POD values for these two types of experiments will lead to better expectations for adapting NDI systems from the laboratory to the field for the same detection problem.

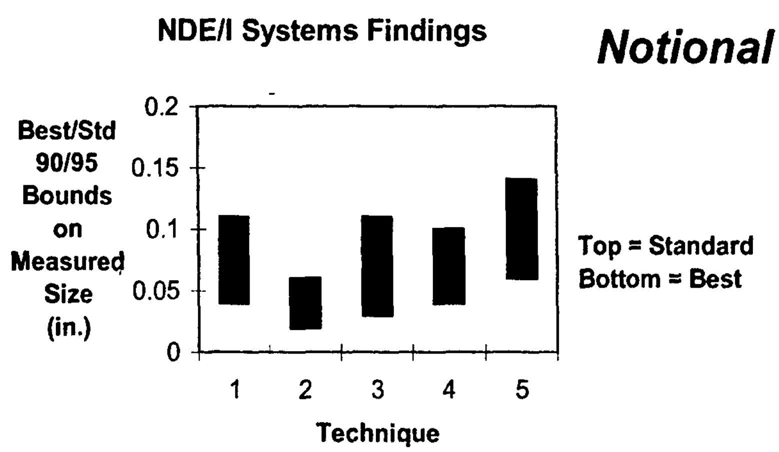

Figure 9 Corrosion detection technology assessment – comparison of NDE/I techniques

From a structural maintenance prospective, it is important to detect the presence of corrosion early enough through fleet surveillance techniques so that cost-effective decisions can be made about controlling the potential for damage. Corrosion detection NDI systems used in surveillance programs must have a high degree of reliability and a low occurrence of false calls to be valuable to the maintenance planner. Schemes in addition to that than shown in Figure 9 have to be devised to provide structural and maintenance engineers with a clear picture of the relationships between detection reliability and false call rates.

3. Concluding Remarks

The uses for NDI systems are widespread and pivotal in the development of cost effective structural maintenance programs. NDI systems provide the basis for surveillance programs that seek to detect anticipated in-service damage before it reaches critical levels in structural components. These systems also provide surveillance for detecting unanticipated in-service damage induced by fatigue loading and/or environmental attack, so that sufficient time is available for developing timely and cost-effective strategies for minimizing fleet wide costs. If hidden damage can be detected by NDI systems, significant cost savings also result since major maintenance costs are involved in disassembling and reassembling airframes, especially when the probability of crack or corrosion damage occurring is low.

To reduce the overall inspection burden, maintenance managers must strive to automate inspection systems and processes. The outcome of automation is to increase the POD, while enhancing the chance that the inspection will be conducted properly. The NDI research community needs to concentrate on increasing the inspection capability to eliminate disassembly of multi-layer structures.

Based on the results of the Automated Corrosion Detection Program [References], a demonstrated method now exists for assessing the reliability of detecting hidden corrosion. This method is based on the method that has been successfully used to assess the capability for a NDI system to detect cracks in either airframe or engine structures. This demonstrated method provides independent quantitative measures of NDI system performance/capability (POD, false calls) in terms of the selected corrosion metric. The Military Handbook 1823 based method assures that a given level/type of corrosion damage is below a target limit, while reducing the number of false calls, thus reducing the cost of disassembly when no corrosion is present. What is now needed to complement the assessment method is a clear definition of economical maintenance or structural limits for the allowable levels of corrosion damage in order to set the POD conditions to meet the target limit.

4. References

1. Lincoln, J. W., "The Findings of the Aging Aircraft Technologies Team", presented at the 1998 USAF Aircraft Structural Integrity Program (ASIP) Conference, Dec. 1998, San Antonio, TX
2. Grimsley, F.M., Lincoln, J.W., and Zeigler, M.L., "USAF Strategy for Aging Aircraft Structures Research and Development", presented at the NATO Applied Vehicle Technology (AVT) Panel Specialist's meeting on Life Management Techniques for Aging Aircraft, 8-11 October, Manchester, UK

3. Cooke, G., Cooke Jr., G., Kawanishi George, Higginbottom, T., Miller, P., and Wacksman, S., "A Study to Determine the Annual Direct Cost of Corrosion Maintenance for Weapon Systems and Equipment in the United States Air Force", Final Report on Contract No. F09603-95-D-0053, Delivery Order 0006, CDRL No A001, NCI Information Systems, Inc, 6 February 1998
4. Berens, A.P., "What Metric Should be Used to Measure Intrinsic Capability? Is it Only POD and FCP – or is Theoretical?", *Materials Evaluation*, pp. 42, January,
5. Rummel, W.D., and Matzkanin, G.A., *Nondestructive Evaluation (NDE) Capabilities Data Book*, Nondestructive Testing Information Analysis Center (NTIAC), Texas Research Institute Austin, Inc., November, 1997. " His handbook developed for the NTIAC …
6. Hoppe, W.C., Schehl, N., Buynak, C., Gallagher, J.P., Berens, A.P., "From Cracks to Corrosion: The Evolution of a Probability of Detection Approach that Quantifies Corrosion Damage in Aging Aircraft", Proceedings of the 2000 USAF Aircraft Structural Integrity Program (ASIP) Conference, Dec. 2000, San Antonio, TX
7. Military Handbook 1823, Nondestructive Evaluation System Reliability Assessment (1994).
8. Hoppe, W.C., Pierce, J. L., Schehl, N., Ko, R., and Buchanan, D., "Results from the Hidden Corrosion Detection Evaluation on the Automated Corrosion Detection Program – Probability of Detection", Proceedings of 5th NASA/FAA/DoD Aging Aircraft Conference, 10-13 September, 2001, Orlando, FL
9. Schehl, N., Hoppe, W.C., Berens, A.P., and Ko, R., "Evaluation of an Intergranular Corrosion Detection Method on the Structural Repair of Aging Aircraft Program" Proceedings of 5th NASA/FAA/DoD Aging Aircraft Conference, 10-13 September, 2001, Orlando, FL
10. Hoppe, W. C., "Hidden Corrosion Detection Technology Assessment," Second Joint NASA/ FAA/DoD Conference on Aging Aircraft, NASA/CP-1999-208982, (1998), pp 349 – 358.
11. Hoppe, W. C., Schehl, N., Finch, J., "Specimen Development and Selection for Hidden Corrosion Detection Technology Assessment", Evolving and Revolutionary Technologies for the New Millennium, 44th International SAMPE Symposium/Exhibition, May 23-27, 1999 pp. 820 – 833.
12. Hoppe, W. C. and Pierce, J.L., "The Evaluation of Hidden Corrosion Detection Technologies on the Automated Corrosion Detection Program", Fourth Joint DoD/FAA/NASA Conference on Aging Aircraft – Proceedings, 15-18 May 2000.
13. Hoppe, W.C., Schehl, N., Buynak, C., "An Evaluation Methodology for the Assessment of Corrosion Detection", summary to be published in ASNT Fall 2000 Conference Proceedings